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SATELLITE NAVIGATION AND LOCATION SYSTEMS

Background paper 4

***The full list of the background papers*:**

1. The Earth and its environment in space
2. Disaster prediction, warning and mitigation
3. Management of Earth resources
4. Satellite navigation and location systems
5. Space communications and applications
6. Basic space science and microgravity research and their benefits
7. Commercial aspects of space exploration including spin-off benefits
8. Information systems for research and applications
9. Small satellite missions
10. Education and training in space science and technology
11. Economic and societal benefits
12. Promotion of international cooperation

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PREFACE

The United Nations General Assembly, in its resolution 52/56, agreed that the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE III) should be convened at the United Nations Office at Vienna from 19 to 30 July 1999 as a special session of the Committee on the Peaceful Uses of Outer Space, open to all Member States of the United Nations.

The primary objectives of UNISPACE III will be:

(a) To promote effective means of using space technology to assist in the solution of problems of regional or global significance;

(b) To strengthen the capabilities of Member States, in particular developing countries, to use the applications of space research for economic and cultural development.

Other objectives of UNISPACE III will be:

(a) To provide developing countries with opportunities to define their needs for space applications for development purposes;

(b) To consider ways of expediting the use of space applications by Member States to promote sustainable development;

(c) To address the various issues related to education, training and technical assistance in space science and technology;

(d) To provide a valuable forum for a critical evaluation of space activities and to increase awareness among the general public regarding the benefits of space technology;

(e) To strengthen international cooperation in the development and use of space technology and applications.

As one of the preparatory activities for UNISPACE III, the Office for Outer Space Affairs of the Secretariat has prepared a number of background papers to provide Member States participating in the Conference, as well as in the regional preparatory meetings, with information on the latest status and trends in the use of space-related technologies. The papers have been prepared on the basis of input provided by international organizations, space agencies and experts from all over the world. A set of 12 complementary background papers have been published and should be read collectively.

Member States, international organizations and space industries planning to attend UNISPACE III should consider the contents of the present paper, particularly in deciding on the composition of their delegation and in formulating contributions to the work of the Conference.

In the preparation of the present paper, contributions from the following organizations have been used: International Civil Aviation Organization, the World Meteorological Organization, the European Space Agency, the International Mobile Satellite Organization, the Department of Space of the Government of India, the Indian Space Research Organization and the Russian Space Agency.

The assistance of M. J. Rycroft (International Space University, Strasbourg, France, and Cambridge University, United Kingdom of Great Britain and Northern Ireland) as technical editor of background papers 1-10 is gratefully acknowledged.

SUMMARY

The Global Navigation Satellite System (GNSS) is a space-based radio positioning system that includes one or more satellite constellations, augmented as necessary to support the intended operation, and that provides 24-hour three-dimensional position, velocity and time information to suitably equipped users anywhere on, or near, the surface of Earth (and sometimes off Earth). There are two core elements of satellite navigation systems: the Global Positioning System (GPS) (operated by the United States of America) and the Global Orbiting Navigation Satellite System (GLONASS) (operated by the Russian Federation).

Satellite navigation uses satellites as reference points to calculate positions accurate to within metres. With advanced forms of satellite navigation, measurements can be made down to the centimetre level.

The main advantages of satellite navigation and positioning are economy and better services, largely but not limited to the transport area. New applications are emerging frequently in a wide variety of sectors as technology continues to evolve. The future of satellite navigation is unlimited.

GNSS receivers have been miniaturized to just a few integrated circuits and are becoming very economical, making the technology accessible to virtually everyone. GNSS technology has matured into a resource that goes far beyond its original design goals. Currently, scientists, sportsmen, farmers, soldiers, pilots, surveyors, hikers, delivery drivers, sailors, dispatchers, lumberjacks, firefighters and people from many other professions are using GNSS in ways that make their work more productive, safer and sometimes even easier. GPS equipment is being built into cars, boats, planes, construction equipment, movie-making gear, farm machinery and even laptop computers. Soon, satellite navigation will become a universal utility.

The fast-growing worldwide market for GNSS receivers is currently approaching an annual turnover of 2 billion United States dollars ($) and is expected to reach $8 billion by 2000. Conservative estimates for the markets of value-added services indicate that they will be at least of the same size as the receiver market.

Both GPS and GLONASS were developed for military purposes and remain under the military control of the United States and the Russian Federation. However, the use of these two existing military satellite navigation systems has been offered free of charge to civil users. Currently, neither system meets the requirements of all user categories, civil aviation in particular, and both need to be enhanced with system augmentations; preparatory work towards a follow-on system has been initiated.

While the implementation of existing systems in the development of a future global satellite navigation system can now get under way, there are still a number of political, institutional, legal and economic problems to be resolved before any new type of system can be deployed.

I. BRIEF HISTORY OF RADIO NAVIGATION SYSTEMS

1. Radio navigation had its origin in the 1920s. The earliest systems were based simply on the ability of a radio receiver with a loop antenna to determine the direction of arrival of a radio signal and the relative bearing to the transmitter. Later, several radio navigation systems relied on ground transmitters sending modulated signals characteristic of the direction of transmission. Other radio systems determined the direction and/or range from the navigator equipment to a fixed transmitter.

2. There have also been long-range navigation systems that measure the difference in time between signals received from synchronized pairs of transmitters at different locations or phase differences between continuous-wave transmissions from pairs of transmitters.

3. Ground-based navigation transmitters operate over a wide range of frequencies. Low-frequency radio waves are not easy to modulate, and are subject to errors due to the ionosphere and weather disturbances. High-frequency radio is limited to line-of-sight range, so that many on-land transmitter sites are required and transmitters are impossible to position at sea. A satellite, however, is an ideal location for a radio navigation transmitter, and a constellation of satellites, in appropriate orbits, can cover Earth with navigation signals. Satellites were first used for position finding in a system called TRANSIT.

II. OVERVIEW OF SATELLITE NAVIGATION

A. Global Positioning System

4. GPS is the most recognized term describing satellite navigation systems; however, it is only one of several elements falling under the umbrella of GNSS. Satellite navigation uses satellites as reference points to calculate positions accurate to a matter of metres. With advanced techniques and augmentations, satellite navigation can make measurements down to the centimetre level.

5. GNSS receivers have been miniaturized to just a few integrated circuits and are becoming very economical, making the technology accessible to virtually everyone. GPS is currently being built into cars, boats, planes, construction equipment, movie-making gear, farm machinery and even laptop computers. Soon GPS will become a universal utility.

6. Satellite navigation is a space-based radio positioning system that includes one or more satellite constellations, augmented as necessary to support the intended operation, and that provides 24-hour three-dimensional position, velocity and time information to suitably equipped users anywhere on, or near, the surface of Earth (and sometimes off Earth). A satellite navigation system provides users with sufficient accuracy and integrity of information to be useable for critical navigation applications. The GPS system is the first core element of the satellite navigation system widely available to civilian users. The Russian satellite navigation system, GLONASS, which is similar in operation, is another satellite constellation element of GNSS.

7. These systems promise to bring radical improvements to many other systems that have an impact on the lives of everyone. By combining GNSS with current and future computer mapping techniques, the identification and management of natural resources will be improved. Intelligent vehicle location and navigation systems will enable car and truck users to avoid congested freeways and find more efficient routes to their destinations, saving millions of dollars in petrol and tonnes of air pollution. Travel aboard ships and aircraft will be safer in all weather conditions. Businesses with large amounts of outside plants (for example, railroads and utilities) will be able to manage their resources more efficiently, thereby reducing consumer costs.

8. Accurate mapping and surveying is another area in which GPS is expanding. Mapping and surveying companies use GPS extensively. In wildlife management, endangered species are being fitted with GPS receivers and tiny transmitters to help determine population distribution patterns and possible sources of disease.

9. GPS-equipped balloons are monitoring holes in the ozone layer over the polar regions, and air quality is being monitored using GNSS receivers. Buoys tracking major oil spills transmit data using GNSS. Archaeologists and explorers are using the system. The future of GNSS is unlimited. New applications will continue to be created as technology evolves. As the cost of GNSS receivers continues to drop, more and more entrepreneurs will invent further uses for the system.

10. GPS is a satellite-based navigation system developed and operated by the United States Department of Defense. GPS permits land, sea and airborne users to determine their three-dimensional position, velocity and time. The service is available to military and civilian users around the clock, in all types of weather, anywhere in the world.

11. GPS uses the Navigation Satellite Providing Time and Range (NAVSTAR) satellites. The current constellation consists of 21 operational satellites and 3 active spares. The GPS system is now fully operational. Satellites are in orbits with approximately 12-hour periods operating at an altitude of 20,200 kilometres. The orbital constellation consists of six orbital planes, each inclined with respect to the equatorial plane by about 55 degrees. Such an arrangement ensures that at any time there are at least four (and up to 12) satellites above the horizon available for simultaneous measurements.

12. GPS receivers are therefore able to instantly solve four equations to determine latitude, longitude, altitude (with reference to mean sea level) and time. GPS is not only a positioning tool but probably the best timing system available. Atomic clocks inside the satellites stabilize the signals that are transmitted. Those signals allow user time to be determined within an accuracy of 0.1 microsecond.

13. GPS works in very logical steps; each of the orbiting satellites beams a continuous radio signal to Earth, which is received by a GPS receiver in order to derive distances by measuring the travel time of the radio signals. The travel time can be measured extremely accurately because of the very accurate timing devices aboard each satellite, and corrections to the result account for any delays which the signal experiences as it travels through the ionosphere and the atmosphere.

14. The GPS satellite signal contains information used to identify the satellite, as well as the position, timing, ranging data, satellite status and updated ephemeris (orbital parameters). The satellites are identified by either the space vehicle number or the pseudo-random code number.

15. GPS satellites transmit on two L-band frequencies: 1.57542 GHz (L1) and 1.22760 GHz (L2). The L1 signal has a sequence encoded on the carrier frequency by a modulation technique which contains two codes, a precision (P) code and a coarse/acquisition (C/A) code. The L2 carrier contains only P-code that is encrypted for military and authorized civilian users. Most commercially available GPS receivers utilize the L1 signal and the C/A code.

16. P-code users determine their geocentric positions instantly to about 5 metres with a single hand-held satellite receiver. The military has encrypted the P-codes by altering the underlying mathematical formula and only authorized users know what the change is. As a consequence, civilian users cannot observe the P-codes directly.

17. The C/A codes repeat every millisecond and are available to every user. These codes are also usable for positioning but they provide only about 20- to 30-metre accuracy. The military has built another feature into the system: selective availability. The combined effect of selective availability, that is, both clock dither and tinkering with the navigation message, degrades the position accuracy of single-receiver users to about 100 to 150 metres. This is an officially sanctioned policy.

18. GPS is at present wholly financed and operated by the military, but many technological developments of GPS positioning were driven by the civilian sector. Typically, civilian users strive to achieve the highest position accuracy. Some techniques rely on two stations that co-observe GPS satellites simultaneously and provide for an almost unbelievable accuracy of 1 centimetre in 10,000 kilometres. Such accuracy is primarily of scientific interest for studying Earth crustal deformations and tectonic plate motions, for example.

19. While static GPS techniques with stationary receivers are very useful in many cases, GPS works equally well when one or both receivers are in motion, through kinematic GPS techniques. The applications of accurate kinematic positioning are unlimited.

20. The GPS control segment consists of a worldwide system of tracking and monitoring stations. The monitoring stations measure signals from the GPS satellites and relay the information collected to the master control station. The master control station uses the data to compute precise orbital models for the entire GPS constellation. The information is then formatted into updated navigation messages for each satellite.

21. The user segment consists of the GPS receivers, processors and antennas utilized for positioning and timing. The user's receiver measures the time delay for the signal to reach the receiver. By knowing the distance to four points (the satellites) in space, the GPS receiver is able to triangulate a three-dimensional position (latitude, longitude and height).

B. Differential Global Positioning System

22. A system was developed to improve GPS accuracy even further. Differential GPS (DGPS) is GPS with an additional correction signal added. DGPS uses a reference station at a known point to calculate and correct bias errors. The reference station computes corrections for each satellite signal and broadcasts these corrections to the remote GPS receiver. The remote receiver then applies the corrections to each satellite used to compute its fix.

23. DGPS can yield measurements to a couple of metres accuracy in moving applications and even better in stationary situations. That improved accuracy has a profound effect on the importance of GPS as a resource. With it, GPS becomes more than just a system for navigating boats and planes around the world. It becomes a universal measurement system capable of positioning things on a very precise scale.

24. Real-time differential GPS makes use of a base station located over a known control point where it is continuously computing the difference between its known and its reported position every second or so. It then sends this correction information to a radio transmitter, which broadcasts the correction information over an existing broadcast frequency. The GPS receiver of the user needs to have a second radio receiver that will receive the differential broadcast, and that will correct the recorded position for the position recorded 1 or 2 seconds previously. Because the errors in the system, or rover, do not simply jump about randomly, but "fade" in directional patterns, the systems can provide real-time positioning at the required accuracy of 2-5 metres.

25. Carrier-phase GPS is a second method of position determination capable of providing centimetre positional accuracy, and is used extensively in the surveying and geodetic communities for the creation of precise surveying monuments and geodetic controls. It tracks and records the 19-centimetre radio waves, corresponding to the carrier frequency L1, transmitted from the satellites. The receivers are much more complex and expensive than the hand-held code-based GPS receivers. One receiver is placed over a known geodetic survey marker, while a second is placed where the new control point or marker is needed. This technique is rapidly becoming the means of conducting centimetre accuracy surveying for a variety of practical and scientific purposes, including photogrammetry, aerial survey controls, and even measurements of minute movements of Earth plates or volcanic lava domes.

C. Global Orbiting Navigation Satellite System

26. GLONASS has much in common with GPS in terms of the satellite constellation, orbits and signal structure. Both transmit spread spectrum signals at two frequencies in the L-band (1.2 GHz and 1.6 GHz), and have pledged to make a partial set of signals available for civil use without any user fees for at least the next 10 years. The GLONASS satellites are deployed in three orbital planes. GPS satellites transmit at the same carrier frequency using codes that are orthogonal; GLONASS satellites transmit the same code but at different frequencies.

27. Unlike GPS, GLONASS does not have intentional signal degradation for civil use. The differences in the quality of the position estimates available from GPS and GLONASS are mainly due to this purposeful degradation of the GPS signals, known as Selective Availability. Like GPS, GLONASS offers two levels of service. The Channel of Standard Accuracy, available to all civil users, provides horizontal position accuracy of 60 metres and vertical position accuracy of 75 metres. The Channel of High Accuracy is available only to authorized users.

28. GLONASS is still under development. In January 1996, for the first time, the system had a full constellation of 24 working satellites. That year, new GLONASS receivers also began to appear on the market. However, no

satellites were launched in either 1996 or 1997 and the number of operational satellites in the constellation as of the beginning of 1998 stood at 13.

29. The GLONASS constellation is operated by a ground-based control complex. It consists of the system control centre (SCC) and several command tracking stations (CTS) which are placed over a wide area of the Russian Federation. CTS track the GLONASS satellites in view and accumulate ranging data and telemetry from the satellite signals. The information from CTS is processed at the SCC to determine satellite clock and orbit states and to update the navigation message of each satellite. This updated information is transmitted to the satellites via CTS, which are also used for the transmitting of control information.

30. Important benefits could accrue to the users of GPS from the additional signals of an operational GLONASS system. The principal benefit would be in the form of robustness of the combined system in the sense that small perturbations in either GPS or GLONASS are unlikely to have a serious impact on any particular user. The source of this benefit is the increased number of satellites in view. Even with a conservative assumption that GPS and GLONASS each would maintain a 21-satellite constellation, all users are assured of a minimum of eight satellites in view above a 7.5 elevation angle; 99 per cent of the global users are assured of 10 satellites in view; and half the users would see 14 or more satellites.

31. An operational GLONASS would remove a serious concern of current GPS users of a single point of failure, technically or politically. The two systems transmit at different frequencies, offering greater immunity to radio frequency (RF) interference, intentional or inadvertent. Such immunity is further enhanced by the frequency diversity of the GLONASS signals. The consideration of robustness is vital to the use of a system in any regular, ongoing operation, especially one that may entail issues of safety. A characterization of the robustness may take the form of integrity of position estimates, continuity and availability of GNSS service under conservative assumptions regarding perturbations to the operation of the system.

32. To improve GNSS performance to satisfy requirements of critical safety applications, various satellite-based and ground-based augmentations are being developed. One way to provide augmentation coverage over large areas is to use satellites, for example, in geostationary orbit, to transmit differential correction and/or integrity messages to the users. This type of augmentation system includes the European Geostationary Navigation Overlay Service (EGNOS) (European Union), Wide Area Augmentation System (WAAS) (United States) and MSAS (Japan).

D. European Geostationary Navigation Overlay Service

33. In view of the investments made by a large variety of users and with the goal of developing the use of navigational signals, Europe has decided to implement an initial GNSS based on a regional augmentation of GPS and GLONASS and to initiate, in parallel, preparatory work towards a follow-on system.

34. The European contribution to a GNSS is based on the use of navigation payloads on geostationary satellites (two Inmarsat-3 and Artemis of the European Space Agency), and is referred to as EGNOS. The EGNOS system will meet, in particular, civil aviation navigation requirements for all phases of flight, from en route to precision approach and landing.

35. Inmarsat-3 satellites are equipped with navigation transponders to receive navigation signals of both GPS and GLONASS systems from a ground station which are then broadcast to users. The navigation package will provide four different services: (i) integrity monitoring; (ii) geostationary ranging augmentation; (iii) wide area differential corrections; and (iv) precision time reference. The International Mobile Satellite Organization (Inmarsat) intends to provide similar, but enhanced, navigation capability on its future generations of satellites.

36. The second-generation GNSS is expected to be under civilian control, tailored to the long-term needs of civil user communities and designed for improved navigation performance, while still retaining GPS/GLONASS

backward compatibility. From a technical point of view, the second generation of GNSS will represent a significant improvement for civil users. The system will have to be designed to serve the needs of civil users in 2005-2020, and it is anticipated that the demand for improved integrity, accuracy and availability will increase. A future GNSS will have to address the needs of all transportation means, whether on land, railway, sea or air, as well as the needs of space systems. It will most likely include enhanced broadcast capabilities and be associated with complementary communications functions, which will be needed for telematics applications (road traffic reporting and forecasting, as well as fleet management systems) and automatic dependent surveillance for air traffic management. Several system options may be considered for GNSS-2: a low-Earth- orbit or a medium-Earth-orbit constellation, with or without a geostationary-Earth-orbit complement. The second-generation GNSS could be introduced as a supplementary means of navigation in 2005-2010 and later operate as the primary means for all flight phases in 2010-2015. From an institutional point of view, GNSS could be jointly developed with some or all the major partners (specifically the United States and the Russian Federation), or independently by the European Union on either a regional or global basis.

III. RELATED SYSTEMS

A. Search and rescue system

37. The International Search and Rescue Satellite System (COSPAS-SARSAT) consists of a constellation of satellites in polar orbit and a network of ground receiving stations that provide distress alert and location information to appropriate rescue authorities for maritime, aviation and land users in distress.

38. The COSPAS-SARSAT system provides distress alert and location data to rescue coordination centres, to beacons at a frequency of 121.5 MHz within the coverage area of COSPAS-SARSAT ground stations (local user terminals), and to beacons operating at 406 MHz and which may be activated anywhere in the world. Complete coverage of Earth, including the polar regions, can be achieved using simple emergency beacons to signal distress.

39. There are three types of radio beacons, namely aviation emergency locator transmitters, maritime emergency position-indicating radio beacons and personal locator beacons. The beacons transmit signals that are detected by COSPAS-SARSAT polar-orbiting spacecraft equipped with suitable receivers. The signals are relayed to COSPAS-SARSAT local user terminals which process the signals to determine the beacon location. Alerts are then relayed, together with location data, via a mission control centre (MCC), either to another MCC or to the appropriate search and rescue point of contact or rescue coordination centre.

40. Doppler location (using the relative motion between the spacecraft and the beacon) is the means used to locate these very simple devices. The carrier frequency transmitted by the beacon is reasonably stable during the period of mutual beacon-satellite visibility. The frequencies currently in use are the 121.5 MHz aeronautical emergency frequency, also allocated to distress beacons, and frequencies in the 406.0-406.1 MHz band exclusively reserved for distress beacons operating with satellite systems.

41. Since 1982, the system has been used for over 2,000 search and rescue events, and has been responsible for saving over 7,000 lives worldwide. COSPAS-SARSAT is currently considering the use of a geostationary Earth orbit search and rescue (GEOSAR) satellite capability as a potential enhancement to the existing polar-orbiting system. In recent years, COSPAS-SARSAT participants have been experimenting with 406 MHz payloads on geostationary satellites together with experimental ground stations. These experiments have shown the possibility of almost immediate alerts with identity at 406 MHz. COSPAS-SARSAT has developed a GEOSAR demonstration and evaluation plan.

B. ARGOS

42. ARGOS is a satellite-based location and data collection system dedicated to monitoring and protecting the environment. ARGOS provides the location of any platform equipped with a suitable transmitter, anywhere in the world, to within 150 to 1,000 metres. Data can also be collected from sensors connected to the transmitter. Over 5000 ARGOS transmitters are now operating around the world. The ARGOS system has been operational since 1978. It was established under an agreement between the National Oceanic and Atmospheric Administration (NOAA) of the United States, the National Aeronautics and Space Administration of the United States and the Centre National d'Études Spatiales (French National Centre for Space Studies).

43. The system utilizes both ground- and satellite-based resources to accomplish its mission. They include instruments carried on board the NOAA polar-orbiting operational environmental satellites, receiving stations around the world and major processing facilities in France and the United States. The fully integrated system works to locate conveniently and deliver data from the most remote platforms to the user desktop, often in near real time.

44. ARGOS is easy to use. A transmitter starts sending signals as soon as it is switched on. One of the system satellites collects the data and retransmits them to the ARGOS centres for processing. Accessing data is just as easy. The results can be retrieved from anywhere in the world by public data networks, often within 20 minutes of transmission.

45. Another attractive feature of the ARGOS system is the small transmitters: the average daily electric current required is as low as a few milliamperes; miniaturized models can be as compact as a small matchbox, weighing as little as 20 grams. Such features mean that ARGOS can be used to track small animals.

46. ARGOS is used to collect data and provide locations for many applications involving environmental protection, including tracking fishing-vessel fleets throughout the world, monitoring the movement of hazardous or dangerous materials, monitoring pipeline systems for leaks or the failure of protection systems, monitoring oil spills or predicting spill movements, and monitoring other types of pollution.

47. India has been using its own Indian National Satellite (INSAT) platforms to obtain meteorological data from unattended remote locations by installing a data relay transponder on board its geostationary satellites. Recently the use of the data collection platforms has also been extended to monitor flood levels in some of the major rivers of the country.

C. DORIS

48. The DORIS (France) system comprises an on-board package, a beacon network and a control and data-processing centre to perform its dual mission of spacecraft orbit restitution and ground beacon location. It is based on the accurate measurement of the Doppler shift on radiofrequency signals emitted by ground beacons and received on board the spacecraft. Measurements are made on two frequencies, 2036.25 MHz for accurate Doppler measurement and 401.25 MHz for ionospheric correction. The 401.25 MHz frequency is also used for measurement time-tagging and auxiliary data transmission.

49. Selection of an uplink system allows for fully automated operation of the beacons and easy communications links for the overall system, the data being centralized through the satellite and its ground segment to the DORIS data-processing centre. DORIS on-board is currently flying on the SPOT-2 and SPOT-3 Earth observation satellites and TOPEX oceanography satellite, and is scheduled to fly on SPOT-4 in 1998 and ENVISAT, SPOT-5 and TOPEX follow-on satellites.

50. The ground segment is shared by all DORIS missions. The orbit determination beacons are deployed in a dense worldwide network. For the point-positioning mission of DORIS, specific ground location beacons are available and are installed according to different user needs. They are field-packaged and equipped with autonomous power supplies.

D. Satellite Laser Ranging

51. Satellite Laser Ranging (SLR) is a technique to measure the range or distance between a laser station on Earth and an orbiting satellite equipped with special mirrors (retro-reflectors), to a precision of less than 1 centimetre. When multiple laser stations are globally distributed and collect data from the same satellite, the precise position of that satellite can be determined along with the positions of the laser stations. That technique is called precision orbit determination. By tracking satellites for several years, not only can the distance between the laser stations be calculated to a few millimetres, but also the rate of motion between the lasers can be monitored to the same precise level. SLR data are also used in numerous other scientific applications, including studies of the Earth/atmosphere/ocean system, geophysics and transferring time standards between continents.

52. The precision of the measurements is a function of the laser tracking system and the satellite retro-reflector array, and may be at the level of 1-3 millimetres, as is the case for the Laser Geodynamic Satellite (LAGEOS). Such precision is achieved through statistical compression of the data.

53. The applications of SLR data from geodetic satellites include detection and monitoring of tectonic plate motions, crustal deformation, Earth rotation and polar motion; modelling of the spatial and temporal variations of the Earth gravitational field; determination of basin-scale ocean tides; monitoring of millimetre-level variations in the location of the centre of mass of the total Earth system (solid Earth/atmosphere/oceans); establishment and maintenance of the International Terrestrial Reference System; detection and monitoring of post-glacial rebound and subsidence; and monitoring the response of the atmosphere to seasonal variations in solar heating.

54. SLR data from remote sensing satellites combined with data from several other tracking techniques together will yield accurate ocean basin topographic maps. The data will permit quantitative studies of changes in ocean currents, which are crucial to understanding global climate change. SLR data will also be used to calibrate the radar altimeters on board the spacecraft. In addition, SLR has proven to be a cost-effective means of providing fail-safe redundancy to spaceborne radiometric tracking systems such as GPS, DORIS and precise range and range rate equipment (PRARE).

55. SLR data from positioning satellites is used to improve the accuracy of the International GPS Service Network and to improve the transfer of time between the GPS and GLONASS satellites and the GPS and GLONASS receivers.

IV. APPLICATIONS OF THE GLOBAL POSITIONING SYSTEM

56. The first and most obvious application of GPS is the simple determination of position or location. GPS is the first positioning system to offer highly precise location data for any point on the planet, in any weather. That alone would be enough to qualify it as a major utility, but the accuracy of GPS and the creativity of its users is pushing it into some surprising realms.

A. Aviation applications

57. GNSS is a main element of the International Civil Aviation Organization communications, navigation, surveillance and air traffic management system providing worldwide navigation coverage to support all phases of flight. With appropriate augmentation systems, GNSS will enable gate-to-gate navigation and all-weather operation capabilities for suitably equipped aircraft. The full implementation of GNSS will offer the possibility of dismantling some or all of the existing ground-based aeronautical systems.

58. By providing more precise navigation tools and accurate landing systems, GNSS makes flying not only safer, but also more efficient. With precise point-to-point navigation, GNSS saves fuel and extends the range of an aircraft

by ensuring that pilots do not stray from the most direct routes to their destinations. GNSS accuracy will also allow closer aircraft separations on more direct routes, which in turn means more efficient use of airspace. The United States Federal Aviation Administration is actively working with DGPS beacons for use in en route navigation, precision approach and landings, and for mapping the precise locations of aircraft on the ground while they taxi to and from runways.

B. Maritime use

59. In general, mariners use GPS for either navigation or positioning, although GPS has recently been applied to surveillance as well. GPS and DGPS are used to provide accurate positioning information that is integrated with other positioning, communications and computing technologies.

60. A maritime real-time DGPS system is being put in place by the United States Coast Guard. It consists of a series of DGPS base stations that transmit over an existing maritime homing beacon system. Plans are to establish a complete series of 45 such DGPS beacons throughout the United States. An operational DGPS beacon system is already working in Scandinavia, and more are being established, some using FM radio sidebands to carry the data, doing away with the need for dedicated beacons.

C. Land transportation applications

61. Many automotive GPS applications fit within the description of intelligent transportation systems (ITS). ITS programmes are intended to: (i) improve traveller safety; (ii) improve travel efficiency by reducing congestion; (iii) save energy though reduction of gasoline requirements; and (iv) lessen the environmental impact of travel.

62. Automobile navigation applications help the driver to make the most efficient routing decisions. Some automobile manufacturers are offering moving-map displays guided by GPS receivers as an option on new vehicles. The displays can be removed and taken into the home to plan a trip.

63. A relatively recent trend is the use of GPS systems in connection with car-mounted cellular telephones to automatically locate cars involved in accidents. In this system, a microcomputer monitors the airbag deployment system installed in new cars. If it detects that the airbag has deployed, the computer calls a service centre over the cell phone of the car, passing to it the last known location of the car as determined by the GPS receiver. The service centre then passes the information to local emergency services, which can then respond.

64. Many companies maintain large fleets of vehicles. Two of the problems associated with maintaining such a fleet consists in knowing the current location and physical condition of any given vehicle. Fleet tracking systems are concerned with addressing those two issues. A fleet tracking system consists of the following:

(a) A vehicle locating device. In some systems, GPS receivers perform that function. Other systems, such as Loran, may be used. Systems such as the Omnitracs service use proprietary satellite-based location systems provided by Qualcomm;

(b) A vehicle-mounted communications device. The vehicle being tracked must be able to transmit its location back to the fleet control centre by some means. Some national fleet management systems use low bit-rate satellite data networks. Others may use some form of cellular telephony. Fleets located in small, geographically contiguous areas may use VHF or UHF two-way radio. The communications module may have additional components allowing the condition of the vehicle to be monitored and short messages to be passed to and from the driver of the vehicle;

(c) A communications network. Data being transmitted from the vehicle may be relayed back to the fleet management by any of several different means. Proprietary satellite communications systems may require dedicated leased data lines from the satellite service provider. Cellular telephone-based tracking systems may rely on the public telephone systems. VHF and UHF radio systems used by police, fire and ambulance systems may use city-owned and -maintained data networks, or possibly packet radio;

(d) A computerized information system. Information on the location and condition of the vehicle is imported into a computer system. The system may be designed to monitor the vehicle autonomously and alert the fleet manager in the event of anomalies.

D. Mapping, geodesy and land surveying (carrier-phase tracking) applications

65. Using GPS to survey and map precisely saves time and money in this most stringent of all applications. Today, GPS equipment makes it possible for a single surveyor to accomplish in a day what used to take weeks with an entire team. And the work can be completed with a higher level of accuracy than ever before.

66. For hundreds of years, surveyors have relied on optical instruments and physical measuring devices. Optical instruments (and newer electronic distance measuring instruments) require a direct line of sight from the instrument to a target. Measuring tapes or chains require that the survey crew physically pass through all the intervening terrain to measure the distance between two points. The big advantage of GPS is that the line of sight does not have to be established between two stations. Thus, surveying can be done in almost all weather conditions or on opposite sides of a mountain. Another advantage is that the accuracy of the collected data is not as dependent on the skill of the instrument operator as previously.

67. Because the line of sight does not have to be established between GPS stations, major cost savings can be realized in large projects involving a large number of survey teams over a limited area. A single GPS receiver can be set up as a reference station which can be used by any number of surveyors, each of which can be working on a separate job. That contrasts with conventional survey equipment, for which at least two people must be working on the same job (one for each end).

68. Carrier-phase tracking of GPS signals has resulted in a revolution in land surveying. A line of sight along the ground is no longer necessary for precise positioning. Positions can be measured up to 30 kilometres from a reference point without intermediate points. Such a use of GPS requires specially equipped carrier tracking receivers.

69. The L1 and/or L2 carrier signals are used in carrier phase surveying. L1 carrier cycles have a wavelength of 19 centimetres. If tracked and measured, the carrier signals can provide ranging measurements with relative accuracies of millimetres under special circumstances.

70. Tracking carrier-phase signals provides no information on the time of transmission. The carrier signals, while modulated with time-tagged binary codes, carry no time-tags that distinguish one cycle from another. The measurements used in carrier-phase tracking are the differences in carrier-phase cycles and fractions of cycles over time. At least two receivers track carrier signals at the same time. Ionospheric delay differences in the two receivers must be small enough to ensure that the carrier-phase cycles are properly accounted for. That usually requires the two receivers to be within about 30 kilometres of each other.

E. Earth science applications

71. A common goal in the Earth sciences is to understand dynamic and often complex processes. While some Earth science investigations aim at extracting an accurate record of the past, GPS provides a unique opportunity to measure ongoing Earth processes in diverse environments. The evolution of Earth science made possible by GPS over the last decade has been dramatic.

72. An initial goal of the Earth science community was to use GPS to test models of plate kinematics predicted by the plate tectonic paradigm. The predictions were based on the interpretation of marine magnetics, hot spot traces

and earthquake focal mechanisms, and are the foundation for much of geoscience research today. Plate kinematic studies with GPS provided detailed observations of plate motions, confirming the geological models, and extending them to regions where constraints from geologic data were weak.

73. The efforts of the Earth science community now focus on using the improved resolution available from GPS to document increasingly complex phenomena in Earth systems. Many of the scientific goals of today would have been unattainable in the early days of GPS studies. Problems being addressed include variations of strain throughout the earthquake cycle, volcanic processes, ice dynamics and sea-level change, and sea-floor geodesy.

F. Meteorological and climate applications

74. GPS has made a huge contribution to the meteorological and climate aspects of environmental monitoring and has a tremendous potential to contribute much more. In the field of operational meteorology, it has already become the prime system for determining position information for balloon soundings, and hence for measuring balloon height and obtaining wind-speed information. Ground-based GPS receivers can provide an estimate of the total precipitable water in the column above the receiver and hence the total latent heat available.

75. Satellite-based receivers can measure vertical profiles of temperature from 5 to 40 kilometres and above using the so-called radio-occultation approach, where the refraction of the GPS signal through the atmospheric limb is determined twice per receiver orbit for every GPS satellite. That can provide as many as 500 profiles per day, uniformly distributed around Earth, and thus offers the exciting prospect of complete global coverage in space and time from a constellation of receivers used in conjunction with a subset of the current costly radiosonde system. This space-based application of the GPS system has been named GPS/MET, and continuing research will extend its capabilities beyond the current highly promising results.

76. GPS/MET will also make a major contribution in climate monitoring in that it can provide long-term, accurate, consistent measurements of mean temperatures on both regional and global scales, which are very difficult or impossible to make from Earth-based sensors. Measurements of stratospheric temperatures will contribute to an understanding of the ozone problem, particularly with respect to predicting the formation of polar stratospheric clouds in conditions of extreme cold. Data from GPS limb sounding may also be useful in the study of gravity waves that transport energy and momentum throughout the middle atmosphere, thereby contributing further to global change research.

77. In the area of data collection, the ARGOS system on the polar-orbiting meteorological satellites and the data-forwarding capabilities of the geostationary satellites are indispensable for the collection and location of environmental data for a variety of applications from fixed and moving platforms around the globe.

G. Atmospheric sensing and sounding

78. The GPS signal is sensitive to the refractive index of the atmosphere. This index is a function of pressure, temperature and moisture. Therefore, GPS can be used to sense properties of the atmosphere. Since small amounts of atmospheric water vapour significantly affect GPS signal propagation velocities, GPS is especially well suited for sensing atmospheric water vapour, which plays a major role in atmospheric processes ranging from global climate change to micrometeorology.

79. While atmospheric sensing techniques with GPS have been developed to achieve better vertical surveying accuracies, future research regarding the use of GPS to monitor atmospheric water vapour may benefit solid Earth science as well. Permanent GPS stations for weather monitoring are now under development. Those stations will enhance the current crustal deformation networks, and improved understanding of atmospheric water vapour may lead to additional improvements in GPS surveying. Data from the atmospheric stations will be made available for high-accuracy GPS orbit determination and may provide more accurate GPS orbits.

80. Kinematic GPS techniques can be used to locate aircraft accurately in flight. If the position of the aeroplane, and more importantly its vertical acceleration and tilt, can be monitored with GPS, airborne gravimetric measurements can be corrected for non-gravitational accelerations. Once it is possible to correct airborne gravimetric measurements to the order of 1 milligal with 1-kilometre resolution, then airborne gravimetric data will become a very useful and powerful tool for scientific research and natural resource exploration.

H. Agriculture

81. Recently farmers have gained access to site-specific technology through GPS. GPS can identify the location of farm equipment to within a metre of an actual site in the field. The value of knowing precise locations to within a few centimetres is that: the location of soil samples and laboratory results can be compared to a soil map; fertilizer and pesticides can be prescribed to fit soil properties (clay and content of organic matter) and soil conditions (relief and drainage); tillage adjustments can be made as conditions across the field vary; and yield data across a field can be monitored and recorded.

82. A computerized soil map of a specific field on a computer fitted to a tractor along with GPS can tell farmers where they are in the field and give them the opportunity to adjust the seeding rate as they go across their fields. Using GPS along with a digital drainage map, farmers can apply pesticides more safely. The spraying equipment can be pre-programmed to turn off automatically when it reaches a distance limitation, or zone of a drainage feature. Additionally, farmers can pre-program the rate of pesticide or fertilizer to be applied so that only the amount needed determined by the soil condition is applied; this rate can be varied from one area of the field to another, saving money and allowing for safer use of the materials.

83. The use of GPS in making equipment adjustments to different soil types would mean higher yields and safer production at lower costs. This part of precision farming is still in its inception phase. The equipment companies will be announcing tillage equipment with GPS and selected controls tailored to precision farming in the near future.

I. Timing and telecommunications applications

84. As a universal marker, time indicates when things happened or when they will happen. As a way to synchronize people, events, even other types of signals, time helps to keep the world on schedule. And as a way to tell how long things last, time provides an accurate, unambiguous measure of durations.

85. GPS satellites carry highly accurate atomic clocks. In order for the system to work, GPS receivers on the ground synchronize themselves to these clocks. That means that every GPS receiver is, in essence, an atomic accuracy clock. Astronomers, power companies, computer networks, communications systems, banks, and radio and television stations can benefit from this precise timing capability.

86. Because the pseudo-ranging method used by GPS to establish three-dimensional position locations requires a highly accurate time standard, the system is ideally suited for applications that require precision timing and precise time transfer. GPS pseudo-range measurements are based on the transit time of a signal from the GPS satellite to the user. Thus, if the locations of both the satellite and the observer are known, the difference in the user-clock offset from that of the satellite can be readily determined.

87. The time-transfer community was one of the first to realize the benefits of GPS, since a full satellite constellation is not required for most time-transfer methods. In fact, the most accurate method of time transfer to date, known as GPS common-view, relies on the ability of two users on the globe to observe the same GPS satellite simultaneously, despite a large geographic separation. GPS common-view is currently used by the 55 international timing centres that are charged with the task of maintaining International Atomic Time and Universal Time Coordinated (UTC) throughout the world.

88. GPS is also increasingly utilized by many telecommunications companies to synchronize their land-based digital telecommunications networks. Most often, these users compare a reference clock directly to GPS time by viewing one or more satellites, rather than transferring time from one reference clock to another.

89. Precise GPS timing also has the potential to improve mobile cellular communications significantly. Currently most cellular telephone networks are subject to transmission degradation as a call is transferred from one cell channel to another; if all the cells of a network used the same channel, the problem would be eliminated. This can be accomplished by providing each cell with a unique code rather than a unique frequency using a technique known as Code Division Multiple Access (CDMA). Major CDMA manufacturers have recognized GPS as an effective way to provide the precise time synchronization required by their systems. Timing accuracies similar to those required for digital networks are sufficient for this application.

90. Cellular signals are also subject to local conditions in each cell, such as weather or landform geometry, and these may vary from cell to cell. By putting GPS positioning capability into the mobile receiver and by transmitting the position information to the mobile control and operations centre of the mobile system, the network control operations could determine user location and travel direction. With that information available, the network controller can provide optimal handovers as well as real-time dynamic performance optimization for each location. When dealing with small, oddly shaped cells, however, or when trying to map signals and propagation characteristics within a complex area such as an “urban canyon”, accuracy on the order of a few metres in three dimensions may be required.

91. In the future, many information services may require “time-of-day” information to a much higher degree of accuracy than is typical of services today. Universal personal communications services and broadband integrated services digital networks may require this in order to interface with several different types of communications systems to transmit tremendous amounts of digitally packeted information. Timing accuracies of 100 to 300 nanoseconds relative to UTC will probably be needed.

J. Spacecraft uses of the Global Positioning System

92. The application of GPS to spacecraft navigation and control, with its potential for saving spacecraft costs and mission operations, is being introduced into both government and commercial spacecraft systems. GPS is currently being tested or used for several spacecraft applications, including orbit determination, attitude determination, launch and re-entry vehicle positioning and trajectory determination, as well as time synchronization.

93. The use of GPS for real-time determination of orbital parameters provides an economical means of very accurately determining the orbit of a spacecraft. A properly designed, space-qualified GPS receiver can replace several conventional orbital positioning spacecraft sensors, reducing both weight and cost, and in some cases relieving the requirement for worldwide, ground-based stations to track orbital positions. In addition, the orbital parameters determined with GPS can in some cases be input to an on-board control computer and propulsion system to provide autonomous station-keeping. That would remove or reduce the need for mission operations personnel to control the orbital position of a spacecraft from the ground.

94. In recent years, several manufacturers of GPS receivers have started collaborating with spacecraft developers to design GPS receivers for use as attitude sensors on board spacecraft. On-board attitude determination is a requirement for virtually every modern spacecraft, and most also require an automatic attitude-control system. The traditional suite of sensors used for attitude determination range from relatively low-cost magnetometers and horizon sensors to precise gyroscopes, Sun sensors and star trackers. GPS may provide a cost-effective complement or even an alternative to many of those existing systems.

95. GPS also has applications to space launch vehicles as a sensor in the vehicle navigation system and in providing positioning information to ground controllers for range safety purposes. Most range safety tracking for launch

vehicles is currently conducted using a rather elaborate and expensive system of ground tracking radars and associated equipment. GPS-derived trajectory data could be more cost-effective.

K. Mineral prospecting

96. GPS is now extensively used in airborne mineral prospecting, making aerial surveys at an altitude of 100 metres or less and with a close spacing of a few dozen metres between successive flights, using highly sophisticated electromagnetic, magnetic and gravity measurement techniques. Accurate position determination of the flight path is required to assess the magnitude, depth and location of the mineral deposits along the track extension.

L. Public safety

97. GPS used in conjunction with communications links and computers can provide the backbone for systems tailored to applications in urban delivery, public safety and vessel and vehicle tracking. Therefore, police, ambulance and fire departments are adopting GPS systems to pinpoint both the location of emergencies and the location of the nearest response vehicle on a computer map. With such a clear visual picture of the situation, dispatchers can react immediately and confidently. GPS is helping to save human lives.

V. ECONOMIC AND SOCIETAL BENEFITS

A. Needs

98. The world community should play an active role in satellite navigation and position services by participating in the development and exploitation of a global system that answers the needs of all civil users. The reasons for this are threefold:

(a) *Social and economic*. The potential market of the navigation signal is enormous and, even if air transport is currently generating most of the interest in satellite navigation, other sectors, in particular road transport, traffic management and agriculture, will account for most of the revenue in the short to medium term. The advantages of a global satellite navigation system include simplification through the use of a single system that could meet all user requirements and operate worldwide 24 hours a day. A space-based system will also provide improved accuracy of position and velocity measurements, which will lead in turn to a reduction of waiting times, fuel savings, better environmental protection and a reduction in the number of accidents;

(b) *Industrial*. Since satellites have only a limited lifetime, space segments must be continuously maintained and updated. Ground segments must be extended to provide greater geographical coverage and improved services. Both must be supplied by industry. New services stemming from the use of the navigation signal include transportation applications, precision agriculture, public safety, geosciences and recreational activities. The market for GPS receivers, currently evaluated at over $2 billion, will increase to between $8 billion and $9 billion in 2000, and to $50 billion in 2005. The applications share is expected to be 92 per cent for terrestrial (mainly car navigation and consumer/cellular applications), 4.5 per cent for aeronautical, 2 per cent for maritime, and 1.5 per cent for military applications;

(c) *Regulatory*. Certification of a space system poses new challenges to regulators, especially those responsible for services concerned with the safety of life. The relevant authorities must decide on their certification policy for future GNSS.

B. Promotion of international cooperation

99. Satellite navigation lends itself by nature to regional and global cooperation. Indeed, a large degree of cooperation is essential if a seamless multimodal satellite-based radio navigation and positioning system is to be achieved throughout the world. The transition from various ground and space-based systems to a common

satellite-based navigation system will require a great deal of cooperation between international civil authorities, Governments and industry representatives.

100. Possible schemes for GNSS-2 development include: an independent development of a worldwide system by a single country or entity (as is the case today); joint development with some or all the major players (India, Japan, Russian Federation, United States and European Union), or independent development of several interoperable regional systems, with the potential to grow into a global system. Many States have an interest in the development of GNSS technologies. In an effort to expand GPS benefits internationally and progress towards the implementation of GNSS, some organizations have been very active in assisting others with the implementation of GPS and its respective augmentations.

101. Fitting both GPS and GLONASS into current (and in the future GNSS) worldwide application developments will require considerable skill and coordination. Member States are beginning to see benefits from the augmentation of GPS and are taking the appropriate actions to develop a similar capability, nationally or regionally.

C. Issues and concerns

102. In the coming years, the international community must work together if a worldwide seamless navigation system based on GPS/GLONASS augmentation is to become a reality. In the longer term, new frameworks for legislation, regulations, certification, standardization and cost recovery will be needed.

103. It is likely that international organizations, as well as individual nations, would like to keep an independent oversight of the GPS augmentations which they have implemented. This oversight may be accommodated in international or regional agreements.

104. Although the benefits of satellite navigation are well understood and accepted, there is a concern that not all classes of users (aviation, maritime, road vehicles, railways etc.) may be able to inject their requirements into the design of a second-generation system. Another major concern is how the cost of building and operating the system could be split on a fair basis between the different users.